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A Novel Approach to Optimize the Design of Parts for Additive Manufacturing

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Abstract

Additive Manufacturing (AM) is a term used to group the different manufacturing processes that use various techniques, each of which is capable of producing parts made from a wide variety of materials, such as polymers, ceramics, metals, wood, among others. All these technologies allow parts manufacturing by adding successive layers of material which can be liquid, powder or wire. In order to take advantages of the geometric freedom offered by AM, Topological Optimization (TO) is usually used. TO provides the optimal distribution of material for a given request. The main objective is weight reduction, without compromising the original resistance of an existing part produced by traditional processes. Taking advantage of the freedom allowed by the AM process and conciliating it with the CAE features, which allow to simulate the parts behavior when subjected to the expected loads, a new approach methodology was drawn in order to shorten the time needed to optimize parts design for AM. A case study was developed in order to validate the methodology established. The combination of AM and TO revealed promising results, attending to the component efficiency achieved.

Keywords: Additive Manufacturing, Direct Metal Deposition, 3D Printing, Topological Optimization, Part Design Optimization.

1. Introduction

The huge industrial and technological progress disclosed in the last decades has caused the market to feel the need to perform extremely fast solid functional parts capable of being presented to customers [1]. This process became known as rapid prototyping (RP) and this term is currently used in the most diverse industries. RP is a concept often used to describe the technologies that create physical products using digital data [2,3].

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AM is a term widely used for manufacturing processes capable of producing parts by the addition of material in successive layers [4]. Initially, AM (Additive Manufacturing) technologies were considered RP technologies, but over the years, with the development and quality improvement of the products manufactured in these machines, there is a distinction between these two concepts [5]. Nowadays, it is possible to produce final parts using only AM, and many other close to the final design, emerging the term Rapid Manufacturing (RM), which was adopted to distinguish the functional nature of the parts made by this technology [6]. The materials used in AM can be polymers, metals, biomaterials, composite materials, among others. A brief history about AM can be found in [7]. These techniques contrast with subtractive manufacturing methods, such as machining or other cutting processes and are based on completely different principles when compared with welding or casting processes. Moreover, these technologies are defined by the American Society for Testing and Materials (ASTM) in ASTM F2792-12A [8] as a process that joins materials to form objects, from digital data providing of three-dimension (3D) models.

Direct Metal Deposition (DMD) is one of the AM processes, which can be considered as a 3D printing process because this technology is based on the transformation of the material into a solid object. Usually, this technology uses powder or wire as a feedstock which is selectively melted by a focused heat source and consolidated in subsequent cooling to form a layer. The material is arranged layer by layer until the desired geometry is attained. At the end, the base may remain in the component or may be removed by mechanical procedures [9].

This work was developed aiming to establish the guidelines to improve the mechanical strength of structural parts using Topological Optimization. The paper presents the following structure: section 1 provide to the reader a contextualization about the Additive Manufacturing; section 2 presents a literature review about the most recent studies undertaken in the field of the design optimization of parts to be produced by AM; section 3 deals with the methodology used in the development of this work; section 4 presents the corresponding results and discussion; section 5 highlight the main conclusion to be taken from this work.

2. Literature Review

The creation of objects layer by layer started in 1979, when Housholder patented the first description of a process using the sinterization of powder by laser, in which the layers could be solidified selectively [10]. As the processes based on layers began to become better defined, it was evident that there were opportunities to be used industrially [10]. Since 1987, several novel technologies have been developed, such as Stereo-Lithography Apparatus (SLA), Laser Engineered Net Shaping (LENS), Direct Metal Laser Sintering (DMLS), Fused Deposition Modeling (FDM), 3D printing (3DP), among others [11-14]. The development of novel processes continued to be carried out until 1991, when the focus in this field was moved to the improvement of the processes whose had been created earlier. The improvements were focused on increasing the manufacturing speed and also the upsurge and diversification of materials used to manufacture these parts [14]. In 1995, Fraunhofer ILT developed the first device that would give rise to Selective Laser Melting (SLM), following the developments described above. However, Carl Deckard created and patented the first AM system for metal through the selective laser sintering (SLS) process only two years later, in 1997. Despite all these developments, it was only in the early 2000 that machines devoted to metal deposition appeared on the market, with enormous opportunities [15]. Currently, the AM of metal is the main focus of development of these manufacturing methods [16]. AM technologies produce parts by polymerization, fusion or sintering of materials through predetermined layer deposition, without the need for tools and absence of wasted material. The AM allows freedom of shape during the project execution, as it is possible to produce more complex geometries, which may even be impossible to produce using other more conventional process [17]. However, this freedom of shape linked to the manufacturing technique brought new challenges to the part design, allowing for its optimization, which is particularly interesting for industrial sectors where the weight reduction is a critical factor, such as the automotive, aircraft and aerospace industries [18, 19].

Currently, during the execution of a structural project, the simulation through the Finite Element Method (MEF), as well as the use of Topological Optimization (TO), have become essential tasks [20]. In addition, TO has become a very important tool in the design of parts that will be subject to significant loads [21]. The development of a light and efficient product is one of the main drivers behind the increasing use of AM for mass production [22]. TO techniques consist of iterative methods for exploring several possible design solutions, and usually result in components with organic shapes that mimic natural structures [23]. TO calculate the optimal material distribution within a project, by varying the density of its elements, by removing excess material or that it is not necessary to withstand the loads, without harmful occurrences [24]. The optimization algorithm presents a structural layout which describes the major load paths as a density distribution of the creation [25]. The first approach, is the classic optimization which wants to find a distribution able to deal with the minimum density of the global mass, namely, the minimum weight in such a way that support the load without exceeding the maximum admissible displacement. Another approach which has become popular for its efficiency is called SIMP (Solid Isotropic Material with Penalization), or also known as density method. The equations for both models can be seen in [26]. Thus, the last model aims to find a distribution of density ρ, where is imposed a restriction on the maximum volume of material obtained, this being defined as a percentage of the initial volume, with the goal of achieving maximum rigidity. This type of approach is also called the "mass fraction" [26]. The quality of the solution obtained by the TO is another variable and can be adjusted through the mesh refinement. The more refined mesh, the more accurate material distribution is achieved [27]. The combined use of AM and TO is something quite common in industries such as aerospace or automobile [28]. AM and TO allow the creation of light and resistant components design, which may be used in dynamic applications. An example of this is the formation of truss structures, where the weight is reduced and the product performance is maintained. However, in the areas of greatest effort, is used solid material [29].

3. Methodology

The Topological Optimization and integration with other Finite Elements Analysis (FEA) starts to be usual. However, the methodologies used define the computing time needed to reach the best solution. Thus, the methodology to develop this kind of problems was the first concern of this work. The approach followed to develop the best strategy in order to optimize the parts design can be seen in Figure 1.

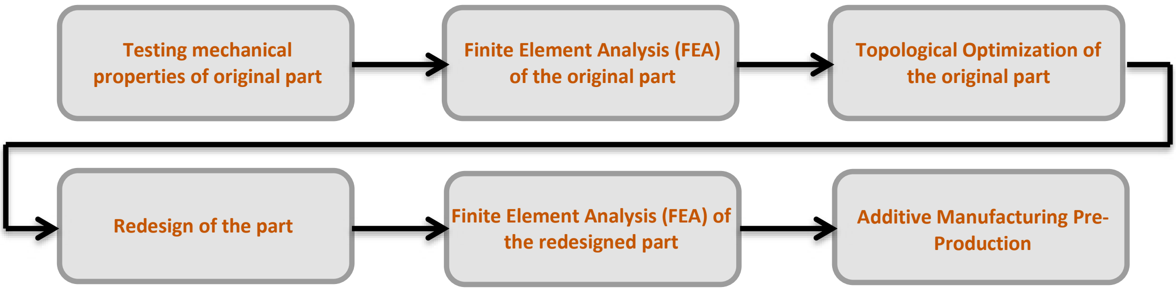

Fig. 1 - Flowchart regarding the approach followed to develop the best strategy in order to optimize the parts design.

The procedure drawn in Figure 1 can be detailed in the following stages: (a) the first consists on performing mechanical tests to the original component, in order to evaluate the maximum strength values admitted by the component, to serve as reference to the next step; (b) after having obtained the admissible maximum stress values, it is necessary to find an adequate mesh. Thus, several iterations will be performed by FEA until the trials present the most approximate values to those obtained in the previous step; (c) the next step is the TO, which is also an iterative process. Regarding the optimization, several aspects need to be defined initially, such as some design restrictions, namely the maximum stiffness or minimum weight; (d) upon completion of the optimization according to the main goals, it is important to define a strategy of approach to interpretation and redesign of the solution obtained; (e) the redesign is also considered an iterative process due to the need of validation through analysis according to the FEA. It is necessary to improve some part regions to reduce stress values, and/or also eliminate stress concentration regions; (f) after having achieved the final shape for the component, it is ready to be produced, however, during this period (pre-production) it is important to select a suitable production process. The need for support structures to aid manufacturing, must be verified in preproduction [30]. For preproduction, other tasks may need to be performed, depending on the evolution state, namely: geometry viability tests, part production, new FEA validation and post-processing. Based on the reasoning previously developed, other variables need be considered before production in series, namely the materials and the additive manufacturing process to be used, as mentioned in [5]. The tools used to perform TO and FEA tasks were HyperMesh and OptiStruct from Altair, available at CEIIA - Centre of Engineering and Product Development, Porto, Portugal. In order to validate the procedure abovementioned, a case study was developed based in an existing component.

4. Results and discussion

Upon completion of the strategy previously mentioned, it was time to practically test it on an existing component. The aerospace industry uses lightweight materials to manufacture most of its components. Aluminium alloys are widely used in this industry, being the alloys from 2000 series and 7000 series the most suitable due to their good mechanical strength and high fatigue performance. The case study selected for this work serves as support in an aircraft door (Figure 2), which is subject to fatigue during its working time, with the induction of compressive stress when the door is closed, and the tensile stress when it is opened. This component is connected to the aircraft structure through eight 4.1 mm diameter holes, where HST315 structural rivets promote the assembly of the part to the aircraft structure. Already the larger hole (diameter 16 mm) works like an eyelet, i.e. where loads are applied. The original part is manufactured in Aluminum alloy 7075-T6, whose mechanical properties can be seen in [31]. The initial component has been tested mechanically for two static loads (Fx = -4.5 kN, Fz = 2.5 kN (Case A) and Fx = 4.0 kN, Fz = 3.0 kN (Case B)). During these trials Rosetta strain gauges were applied to get the maximum installed stress values. In table 1 can be seen the applied loads values, as well as the values obtained for each of the cases (test carried out at a temperature of 25°C, with a speed displacement of 1 mm/min). These values will be used as a reference for further mesh refinement.

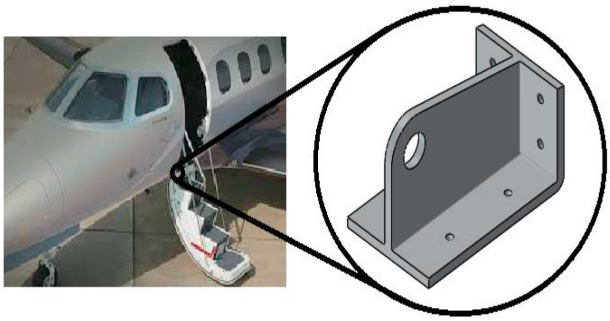

Fig.2 – Aircraft door support.

Table 1 – Maximum stress installed for different loading situations.

Situations tested	Loads (kN)			Stress (MPa)
	F_X	F_Y	F_Z	σ_{max} (Von Mises)
Case A	-4,5	0	2,5	113,27
Case B	4,0	0	3,0	436,73

Regarding the optimization process, some restrictions were taken into consideration, namely hole diameter, hole positioning and installed stress. The properties used as variables were the following: geometry, part volume, part weight and material to be used. In Figure 3 is represented the original component, where blue regions represent design constraints and green regions normal ones, passible to be changed. It is still possible to see that there is a diameter around the holes for rivets and the "eye" that is also considered as a design constraint. This is due to the need to ensure the same global mechanical resistance, which in this case is given for twice the diameter of the hole in question. FEA is an excellent method to simulate real cases of engineering, however, these tools only present accurate results if the mesh is properly set. The number of elements contained in the mesh defines the accuracy degree of the results. Thus, to create a situation as real as possible, the stresses obtained by mechanical tests will serve as a reference. In this way, the mesh must be adjusted so that the stress values obtained numerically are very close to those obtained in the tests. For this, an analysis of convergence will be made, i.e., a mesh refinement iteration will be performed until reaching the desired values by the FEA. In addition to defining the mesh, load (Figure 3, green arrow) and the anchorages (Figure 3, magenta triangles) it is also necessary to define the part material. As previously mentioned the material can be changed in a further stage but, for the first iteration the properties of the material used should be similar to those presented by the original part. (Al 7075-T6 alloy). Figure 4 shows the number of elements as a function of its dimension. There is a huge disparity in the amount of elements and this will be reflected later in the value of the strains obtained. Although, in Figure 4 are represented meshes with a dimension of 0.15 mm, element convergence analysis performed for each of the case studies used only up to 0.4 mm. This is the result of the computational effort involved, as it was found that the computational effort required for smaller meshes was too high and the result obtained did not match the desired requirements.

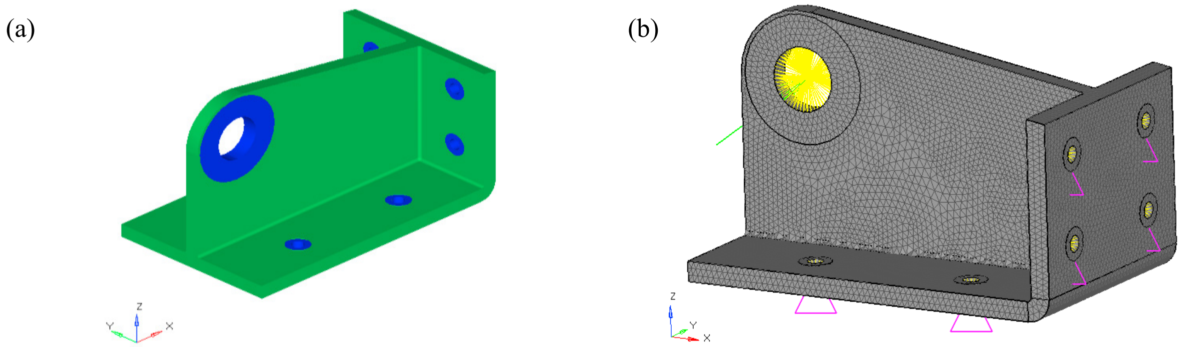

Fig.3 – View of the original part and correspondent restriction (a) as well as mesh distribution and applied loads (b).

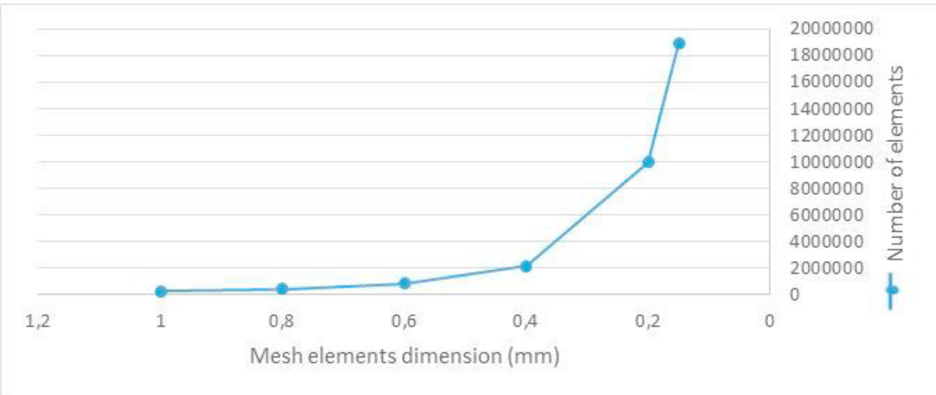

Fig.4 – Increase of the mesh number of elements as a function of the decrease in mesh elements dimension.

In Table 2 are pointed out the stress values obtained in each of the iterations performed, according to loads established for case A. The closest value obtained is highlighted in bold (4th iteration), being needed elements with 0.4 mm to get stress values similar to the reference value. In Table 3 the same reasoning is carried out with respect to case B, and it can be concluded that the value reached in the 3rd iteration is enough to ensure the value of reference.

Table 2 – Iterations performed for case A (F_x = -4.5 kN, F_z = 2.5 kN).

Iteration	Element dimension (mm)	σ_{max} (MPa)	Stress reference Case A (MPa)
1	1,0	91,74	113,27
2	0,80	100,12	
3	0,60	105,86	
4	0,40	**112,83**	

Table 3 – Iterations performed for case A (F_x = 4.0 kN, F_z = 3.0 kN).

Iteration	Element dimension (mm)	σ_{max} (MPa)	Stress reference Case B (MPa)
1	1,0	416,82	436,73
2	0,80	415,96	
3	0,60	**441,21**	
4	0,40	517,04	

In order to perform the part optimization, it is necessary to define the type of loads it will be subjected to. In this case, the goal is to achieve the minimum weight, i.e. reduce weight while maintaining, or even, if possible, reducing the stress values obtained in the mechanical testing of the original part. In this way it was defined as main goals the following: (a) obtain a material reduction volume of 65%; (b) maintain the stiffness to withstand the loads previously pointed out as case A and case B. The software analyses the locations of the part with minor relevance for its resistance regarding the imposed loads, demonstrates the load paths and performs a removal of material to achieve the goal set by the user, in this case, to obtain a part with only 35% of the initial material.

In Figure 5 it is possible to see at a glance the design evolution regarding the load case A. This first redesign might not be the final, because verifications are needed in order to analyze if this redesign meets the initial imposed requirements. Figure 6 depicts briefly the design evolution for load case B. As the parts need to be the same (even supporting different set of loads), both geometries will be analyzed for the two case (A + B), therefore, the shapes must be matched in order to support both sets of loads.

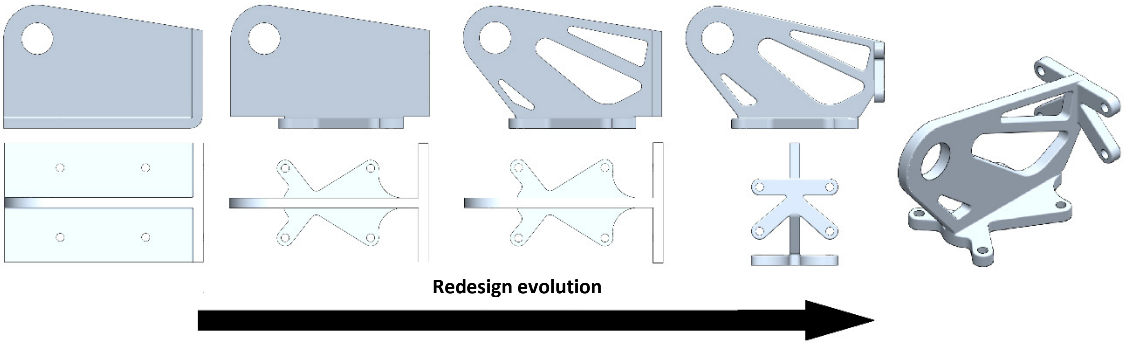

Fig.5 – Evolution of the redesign following the suggestions provided by the TO software (case A).

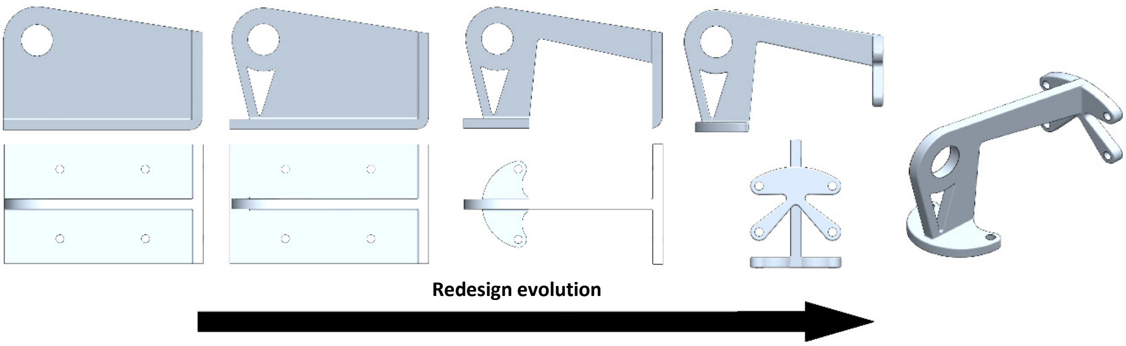

Fig.6 – Evolution of the redesign following the suggestions provided by the TO software (case B).

After the TO and redesign process, it is time to verify by FEA if each new design corresponds positively to each set of loads previously defined. Thus, a new FEA is needed to be performed on both shapes achieved by TO iterative process, conducting to the results shown in Figures 7 and 8. Figure 7a) illustrates the analysis carried out under the set of loads established for case A, and the Figure 7b) depicts the analysis performed under the set of loads agreed to case B. The same is true for the Figure 8, considering the other achieved re-design. Figure 9 represents the final shape obtained after matching the shapes from Figure 7 and Figure 8, regarding the lessons learned through the FEA performed over both shapes. Despite unusual, the shape is perfectly feasible by subtractive processes but additive manufacturing assumes particular relevance in this kind of shape as the waste of material is highly reduced, becoming the manufacturing process much more environment friendly. Sustainable aspects need to take into account the time spent in each process and the cost per hour of the equipment used, factors that are changing drastically nowadays, because of the implementation of DMD as an AM technique is yet in an early stage.

In order to study the material influence in the final solution, two different materials were considered. The first is a material particularly used in this kind of industry, the titanium alloys (Ti). The ASTM offers various alloys suitable for powder metallurgy, which are naturally more suitable for AM. In this way, the first material selected was the titanium alloy ASTM B817. The other material chosen was the AISI 1060 steel. Despite presenting a much higher density when compared to the Al or Ti alloys, steel also has a much higher Young's modulus. By this way, it can be achieved a wider comparison. The properties of both materials are presented in Table 4.

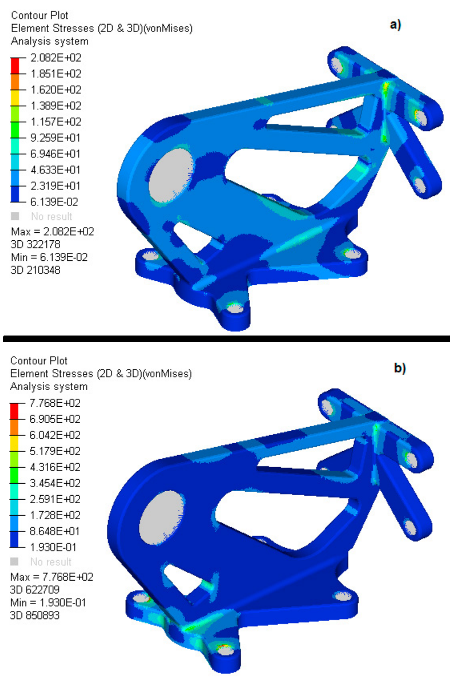

Fig.7 – FEA for (a) set of loads A and (b) set of loads B, regarding the optimized shape obtained taking into account only the set of loads A.

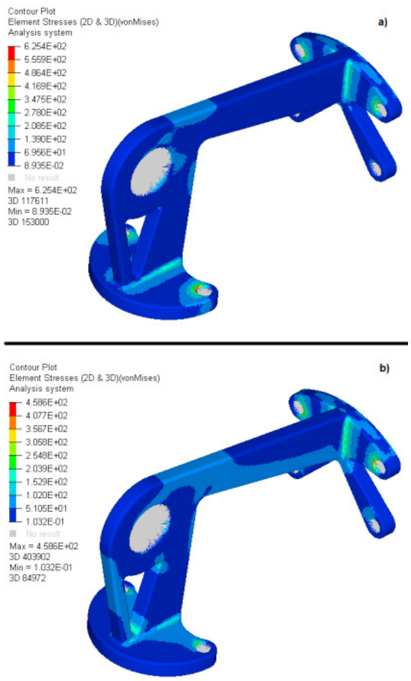

Fig.8 – FEA for (a) set of loads A and (b) set of loads B, regarding the optimized shape obtained taking into account only the set of loads B.

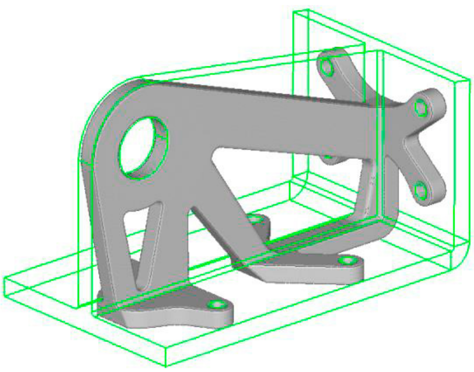

Fig.9 – Final design of the part after several iterations matching the shapes of Fig.7 and Fig.8.

Table 4–Mechanical properties of materials considered as alternative to the Al alloy for this parts regarding the AM process.

Materials	E (MPa)	G (MPa)	σ_{ced} (MPa)	σ_{rot} (MPa)	υ	ρ (kg/m^3)
ASTM B817 Ti alloy (Type I, Grade 2)	100	40	810	900	0.32	4420
AISI 1060 steel	205	80	420	779	0.29	7850

Both cases used in the simulations represent the two most critical situations to which the component is requested in service. There is a huge difference between the results obtained for the cases studied. The case A presents weaker values, lower than those presented by case B. The reference values are very important because serve as guidance before the analysis. Despite mesh refinement being very important, it does not mean that a more refined mesh leads to the best results, as can be seen in the 4th iteration carried out in the case B. Thus, the first step of the diagram shown in Figure 1 assumes particular importance as it establishes the stress reference value, allowing for the correct mesh selection, which can save a lot of time in terms of computational effort.

After achieving the final design, it is important to check the need for holders' inclusion regarding the additive manufacturing process. As a rule, all the slopes exceeding 30 degrees, do not require brackets [32]. The part, depending on the same may be needed more (Figure 10c), fewer (Figure 10a), or no support (Figure 10b). The best criterion to select the part position during the AM process is to choose the smallest volume of support material possible. Regarding Fig.10, the option b) is the most adequate attending that rule.

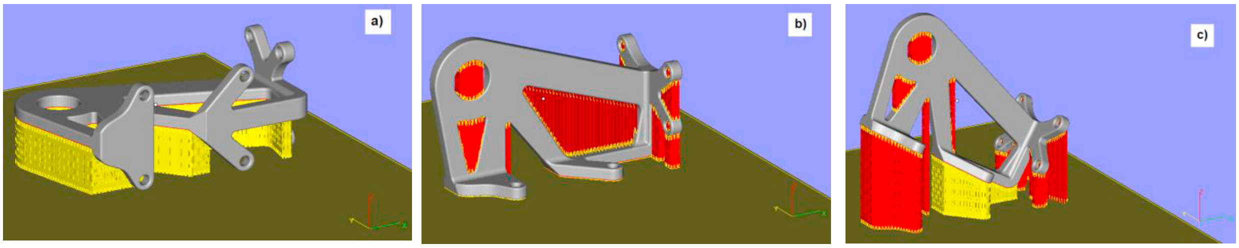

Fig.10 – Influence of part orientation on holding system: (a). horizontal (b) vertical. c) 30° of slope

Before the material replacement, a reduction in stress was expected, something that has been verified, however, the reduction was virtually negligible and the exchange of material for this part is not attractive enough regarding the ratio quality/price.

5. Conclusions

Attending to the main objectives established, the procedure defined in Figure 1 showed to help the designer in seeking the best way to optimize part design through TO. The case study used also allows to realize that establishing two or more loading conditions may result in very different solutions, forcing the designer to adopt some personal strategies to find the optimized solution able to correspond to all loading situations considered. The first step used in the procedure showed in Figure 1 showed to be fundamental for further mesh selection, allowing to save computational work by reducing the element dimension. A further FEA is crucial in order to verify if the optimized shape corresponds effectively to the loading systems previously considered. The designer can opt by organic shapes or more conventional ones, depending on the information given by the TO software and the additive manufacturing machine features. Organic shapes are usually connected to time-consuming manufacturing processes however, AM has brought new paradigms in this case. Thus, TO and FEA used together are a powerful tool in order to save material and reduce weight, factors usually very important for sectors such as aeronautical and automotive industries. These tools also allow for the analysis and eventual replacement of the original material applied, using alloys specially developed for AM process.

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